AFRL-RV-PS-
TP-2013-0001 AFRL-RV-PS-
TP-2013-0001

# TACTICAL SATELLITE-3 MISSION OVERVIEW AND INITIAL LESSONS LEARNED (POSTPRINT)

**Stanley D. Straight, et al.**

**1 March 2013**

**Technical Paper**

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# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. REPORT DATE** *(DD-MM-YYYY)*
01-03-2013

**2. REPORT TYPE**
Technical Paper

**3. DATES COVERED** *(From - To)*
01-06-2004 – 12-06-2010

**4. TITLE AND SUBTITLE**
Tactical Satellite-3 Mission Overview and Initial Lessons Learned (Postprint)

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
Stan Straight, Christina Doolittle, Thomas Cooley, James Gardner, Peter Armstrong,

Richard Nadile, Thomas Davis

**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**

Air Force Research Laboratory
Space Vehicles Directorate
3550 Aberdeen Ave., SE
Kirtland AFB, NM 87117-5776

**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSOR/MONITOR'S ACRONYM(S)**
AFRL/RVEP

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**
AFRL-RV-PS-TP-2013-0001

**12. DISTRIBUTION / AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited. (377ABW-2010-1034 dtd 06-21-2010)

**13. SUPPLEMENTARY NOTES**
"Government Purpose Rights"
24th Annual AIAA/USU Conference on Small Satellites, Utah State University, Logan, UT, 9-12 August 2010.

**14. ABSTRACT**
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**15. SUBJECT TERMS**
Advanced Responsive Tactically-Effective Military Imaging Spectrometer, ARTEMIS, TacSat-3, Hyperspectral, Tactical, Small

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| | | | | | Stanley D. Straight |
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | **19b. TELEPHONE NUMBER** *(include area code)* |
| UNCL | UNCL | UNCL | Unlimited | 16 | |

**Standard Form 298 (Rev. 8-98)**
**Prescribed by ANSI Std. 239.18**

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SSC10-VI-4

# Tactical Satellite-3 Mission Overview and Initial Lessons Learned


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## ABSTRACT

Tactical Satellite-3 (TacSat-3) was successfully launched on 19 May 09, and has provided key insights into hyperspectral imaging capabilities hosted on a small satellite platform. TacSat-3 has given insights into new concepts of operations in the tactical employment of satellites and the balance between on-board processing, automation and performing these functions on the ground. System design decisions made early in the program are traced to on-orbit impacts and contain significant lessons learned for future space missions. In conjunction with the mission partners such as the Operationally Responsive Space Office TacSat-3 has shown lessons in key areas of improving responsive space goals. Specific key areas are the relatively rapid checkout of the spacecraft and lessons from the responsive space development.


## INTRODUCTION

The Tactical Satellite 3 mission was a flight experiment designed to demonstrate tactical and traditional space applications of militarily significant hyperspectral imagery. Additionally, TacSat-3 was developed in the infancy of the Responsive Space movement. TacSat-3 was built to push on increasing the capabilities of a small satellite system within tightly managed programmatic cost and schedule. Finally, it was to demonstrate tactical employment of a space asset, demonstrating the delivery of hyperspectral imagery products directly to a warfighter after being re-tasked within the same pass.

## TACSAT-3 OVERVIEW

The mission's primary payload, the Advanced Responsive Tactically-Effective Military Imaging Spectrometer (ARTEMIS) hyperspectral sensor, rapidly supplies target detection and identification data, as well as information related to battlefield preparation and combat damage assessment. This sensor collects images of objects of interest on the earth and breaks down reflected light into hundreds of spectral bands. These bands can be analyzed to determine the elemental composition of surfaces or objects on the ground. The payload was built by Raytheon Space and Airborne Systems of El Segundo, CA. The spacecraft also includes two other payloads, the Office of Naval Research's Satellite Communications Package, and AFRL's Space Avionics Experiment. The spacecraft bus was built by ATK Spacecraft Systems and Services of Beltsville, Maryland. Two other key components of the Space Vehicle were the Sensor Processor (SP) with hardware built by SEAKR Engineering of Centennial, CO and software developed by Space Computer Corporation of Los Angeles, CA; and a high speed Common Data Link system developed by L-3 Communications, Communications Systems West, Salt Lake City, UT.

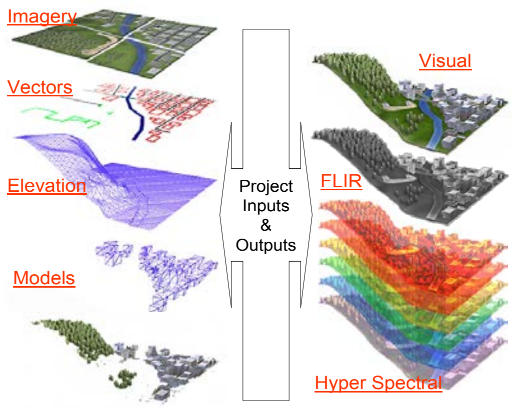



**Figure 1. Hyperspectral Imagery**

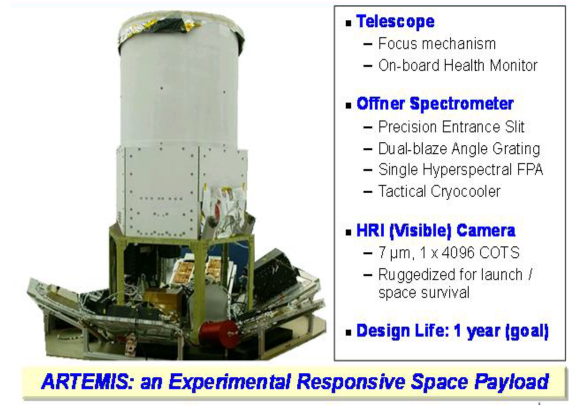



**Figure 2. ARTEMIS Photograph & Description**

### *ARTEMIS Payload*

ARTEMIS is the primary payload for the TacSat-3 satellite. Developed by Raytheon, it is a sophisticated hyperspectral imaging sensor that was designed and built as a rapid development project for AFRL. Designated as the satellite's main demonstration, the hyperspectral imager payload provides target detection and identification information, as well as battlefield preparation and combat assessment data, within minutes of its collection. HSI (hyperspectral imaging) provides unique benefits to the warfighter. The spectral information in each image lends itself to anomaly detection in a given scene, spectral matching of elements within the scene, and ultimately capabilities to distinguish man-made materials from natural materials. HSI uses detailed spectral signatures for every pixel to identify and locate different types of materials, vegetation, or minerals. This capability enables detection of otherwise unseen targets and provides near real-time intelligence data to field commanders.

The innovative ARTEMIS payload covers the visible through short-wave infrared spectrum. Its components include a high-resolution panchromatic imager, telescope, optics, focal plane array, and control/readout electronics. In addition to sensor development and delivery, Raytheon's TacSat-3 responsibilities included integration support and assistance during in-flight calibration verification.

The ARTEMIS payload successfully implemented a number of design and test decisions to meet the program's challenging cost and schedule. These include (1) significant use of commercial off-the-shelf (COTS) and tactical-grade electronic components with minimal redundancy, (2) use of a single spectrometer focal plane array to expedite laboratory alignment and achieve stringent spectral/spatial uniformity, (3) use of a On-Board Health Monitor (OBHM) for trending spectral, spatial, and radiometric performance, (4) implementation of a focus mechanism to achieve on-orbit focus of the sensor, and (5) vicarious techniques for on-orbit spatial and radiometric calibration. These design decisions enabled the successful development and delivery of the ARTEMIS sensor by significantly reducing the cost of hardware components and duration of pre-launch ground testing.

### *TacSat-3 Bus*

TacSat-3 was a first step in reaching the long-term responsive goal of the Operationally Responsive Space Office (ORS) that modular satellite assembly and test be accomplished in a matter of days for a fraction of the cost of current buses. The spacecraft bus includes the main structure; attitude control system (reaction wheels and torque rods); the thermal protection system (heater and blankets); the integrated avionics unit (flight computer); the power system (battery, solar arrays, and wire harness); the primary flight software, which controls and manages the entire space vehicle; and the primary Telemetry, Tracking, and Control link. The TacSat-3 Modular Bus was designed and built by ATK Spacecraft Systems and Services, Beltsville, MD. It is a three-axis stabilized precision pointing bus that provides power, thermal control, communication, and command & control functions for the payloads. The modular bus enables the collection of hyperspectral data by flying a precision profile.

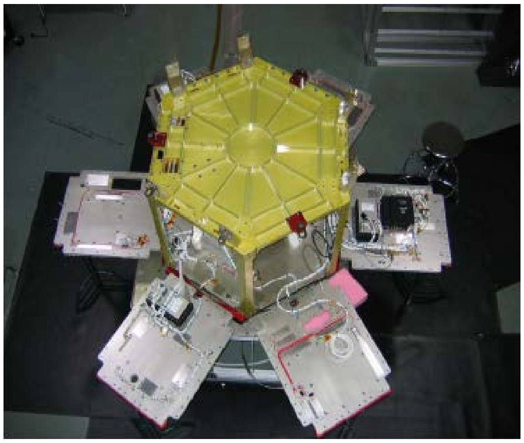


**Figure 3. TacSat-3 Modular Bus**

This profile projects the ARTEMIS entrance slit along the ground at a steady rate to build up the along-track spatial component of the hyperspectral data cube. The bus avionics receive commands from the ground, coordinate the payload activities, and monitor thermal and health status, reacting to the inputs to protect thermal limits needed for payload stability. Other features of the spacecraft design include the adoption of Integrated Systems Engineering Team standard interfaces, that were developed in parallel by a joint government-industry team of engineers; an agile three-axis stabilization system to enable payload sensors to collect precision data on-orbit and downlink processed information in the same orbit pass; a robust power capability with modular power options that can be tailored for specific mission requirements; and a high-strength structure with adaptable interfaces to support a variety of sensor payloads. The on-orbit performance of the bus has been excellent. In particular, the solar panels have exceeded expectations, providing a positive power balance for even the most stressing normal operations.

## LESSONS LEARNED HIGHLIGHTS

Lessons learned can be categorized within 3 main phases of the program: Definition/Acquisition, Integration/Test, and Experiment Operations. A full treatment of the lessons learned would require much more discussion than allowed within this paper, but several highlights for the small spacecraft community are given.

### *Definition/Acquisition Phase Overview*

On 28 Oct 2004, Mr. Peter Teets (Undersecretary of the Air Force, and DoD Executive Agent (EA) for Space) approved the selection of a hyperspectral imaging system as the primary payload for TacSat-3. The concept was born out of a selection process led by AFRL. The main idea was to marry operational user needs with emerging technologies using a small spacecraft. The selection process was created with inputs across all DoD enterprises. The process culminated in a joint service selection.

The goal of quick and low cost acquisition shaped the TacSat-3 program from the beginning. Funding limitations and the initial acquisition strategy dictated that the highest risk component, the HSI sensor, be acquired first. This sensor was acquired before the rest of the satellite system, which necessarily set certain parameters of its design. This was done somewhat in a vacuum with respect to the rest of the satellite system. Interface assumptions became major drivers for the rest of the satellite, and often with detrimental effects. Primary among these were thermal interface assumptions and volume allowed for Guidance, Navigation and Control (GN&C) sensors.

The primary thermal interface between ARTEMIS and the bus was assumed to be adiabatic. While great strides were made to isolate the thermal interface, a truly adiabatic interface was unachievable. The exact magnitude of the impact of this assumption has not been effectively measured. This 'simplifying' assumption and the push for leaner acquisition led to the oversimplification of the thermal modeling for ARTEMIS. This caused an increased workload on the bus contractor (who had to incorporate sensor attributes in a total system model), but more significantly, thermal impacts on optical design were not borne out before the operations phase.

Additionally, the leading acquisition of ARTEMIS resulted in insufficient allocation of volume for required bus GN&C hardware: namely the Inertial Reference Unit (IRU). As geolocation was a key requirement levied on the TacSat-3 system, volume was allocated for key GN&C sensors such as star trackers and the IRU to reduce thermal variability between them and the ARTEMIS boresight. As the instrument design matured, volume had to be allocated earlier to maintain cost and schedule. This allocation was performed without the benefit of knowledge of final volume requirements from the bus design.

The Definition and Acquisition Phase continued with the letting of contracts for the Sensor Processor, the Common Data Link (CDL), and the spacecraft bus. The Sensor Processor is the brains of the ARTEMIS sensor providing the sensor control, data handling and processing, interface management, and data storage. The Common Data Link provided the high speed downlink required for the HSI mission requirements. Finally, the spacecraft bus provided the infrastructure to

meet all the mission requirements: primarily Command & Data Handling (C&DH), Telemetry, Tracking & Control (TT&C), Power, Structures and subsystem (non-ARTEMIS) thermal control. These acquisitions were let through separate contracts centrally managed by AFRL.

The government (specifically AFRL) took on the role as prime system integrator. The mistakes in definition are illustrated by the thermal and volume interface issues raised above, but the power of this approach also allowed for key mission assurance saves later in the mission.

***Definition/Acquisition Phase Lessons Learned Highlights***

As cost and schedule were key drivers, specific risks were taken in the development of the system. A primary cost driver was to utilize industrial grade components versus 'Class S' parts, primarily for schedule reasons and to a lesser extent cost reasons. This was in keeping with the flight experiment nature of the acquisition, but balancing mission assurance risk with cost and schedule became a major area for lessons learned. We were able to balance these to field a successful mission.

Within the program office, significant review of "COTS parts" (Commercial Off The Shelf parts) was a primary theme throughout design and build of the TacSat-3 system (as well as I&T and Operations). As it turns out, key themes revealed themselves throughout, such as:

1. Identify highly susceptible systems and avoid 'risky' parts/subsystems in those areas.
2. Use targeted simple redundancy where possible in limited circumstances.
3. Proper and effective communication of risk acceptance/tolerance to contractors is critical. As well as, government understanding of risk prioritization impacts on cost, schedule, performance and mission assurance.
4. Radiation susceptibility testing and analysis can be effective tools if implemented judiciously.

First, establish or know your mission's risk posture sufficiently to locate and avoid 'risky' parts/subsystems in key areas. For space flight experiments in AFRL, this is primarily the TT&C and C&DH subsystems. Having a rock solid link to the ground is a basic essential with no other work-arounds. Redundant systems are not required (and often specifically avoided due to added complexity), but demonstrable high level technology readiness is required. Similarly, the Command and Data Handling subsystem must be of a high enough reliability level to allow for the return of critical telemetry and receipt of commands. Knowledge gained from a failed flight experiment is as valuable as a successful flight experiment.

Second, targeted redundancy of the ARTEMIS cryocooler electronics was used to reduce the risk exposure of radiation effects on the primary mission. Two sets of cryocooler electronics were flown with a simple relay switch between them. Analysis of the predicted, margined radiation environment showed an unacceptable risk to the electronics failing before a year on-orbit. It is telling however, that the switch has yet to be exercised (to date) as the electronics have not had any on-orbit failure. Redundancy is a limited option for small spacecraft and should only be utilized when there are sufficient mass/power margins and the introduction of redundancy does not reduce total system reliability. Total system reliability can be reduced by the switching mechanism, whose reliability directly reduces total system reliability.

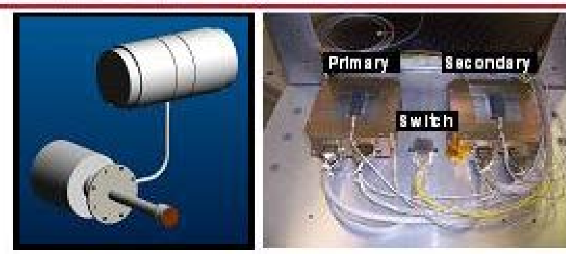



**Figure 4. Tactical Cryocooler and Redundant Cryocooler Electronics**

Third, proper and effective communication of risk acceptance/tolerance to personnel making build/design decisions is absolutely essential. These communications require thorough descriptions and discussion of risk definitions among all stakeholders. Risk definition may be widely different between two organizations or even sub-organizations. Risks also have different meanings in different contexts. For instance, the spacecraft contractor's original C&DH system was deemed too risky, which is why the option to provide a more robust system was accepted as part of the winning bid. AFRL was willing to take other risks throughout the system, but the tolerance in this particular area was much less as it is a critical subsystem. As the proposed increased robustness in the C&DH was determined to be unworkable, a major trade study in decreasing risk in this area was undertaken. At the time, increasing the robustness was seen to be necessary for minimally acceptable mission assurance,

but contrary to the originally stated higher priority of controlling cost and schedule. Effectively communicating priorities is important, but often these priorities are based upon a set of assumptions. In this instance, the government's assumption of minimizing system risk on the C&DH even in the light of cost/schedule impacts was not effectively communicated. Part of this was due to inexperience on the government team's side, and the learning of the implications for the stated risk priorities. As AFRL goes forward with future flight systems, the authors propose the development of a common risk posture for flight experiments. While this risk posture should not be rigidly applied in all circumstances, it would provide both government and contractors a basis for understanding assumptions and management of risk.

Finally, testing and analysis for radiation susceptibility (a key component of small satellite reliability) can be effective tools if implemented carefully. A key component in the TacSat-3 system was the high speed interface between the Sensor Processor and the Common Data Link modem. To satisfy the legacy design of the CDL system and provide sufficient data throughput, a high speed link was required. This link is well established for terrestrial and airborne systems, but had no spaceflight heritage. Implementation on the Sensor Processor (SP) side was originally specified to be within an existing COTS component, and implementation on the CDL side was within an FPGA (Field Programmable Gate Array). As FPGA architectures in space have been well characterized, risk was deemed to be low for that interface. However, the 'COTS' part had no known analogue. AFRL chose to push for radiation testing as a risk mitigation effort. The 'COTS' part failed at very low particle energy levels (2 MeV). This failure forced a redesign (to the FPGA implementation) of the Sensor Processor high speed link to CDL, and likely saved the mission.

### *Integration And Test Phase Overview*

A key feature of the AFRL space flight mission assurance process is the reliance on independent Integration and Test at the Space Vehicle level. While different programs have different structures and approaches to integration, the common denominator is system level test performed by an independent AFRL/contractor team. Independence is carried throughout the program, and the AI&T (Assembly, Integration and Test) Team Lead reported directly to the Program Manager and was equal to the Chief Engineer (head of the government engineering team). The intent of this independent test paradigm is to allow for technology development discovery as well as demonstrating a significant cost/schedule savings over traditional programs while maintaining high levels of mission assurance. Additionally, significant synergies in cost, schedule and risk savings are realized by having requirements owners (government engineering) and requirements verification located within the same facility. TacSat-3's original AI&T plan called for the complete integration and test of sub-components of ARTEMIS, the SP, the CDL radio, secondary payloads, the Ground System and the spacecraft bus at Kirtland AFB, NM.

The TacSat-3 payloads and modular bus were designed, fabricated, and assembled at their respective contractor locations and then delivered to the AFRL Aerospace Engineering Facility (AEF) at Kirtland AFB, NM for integration and space qualification testing. A joint team of AFRL and ATA Aerospace engineers and technicians assisted by Raytheon, ATK, L-3 Communications, and other team members assisted in completing the activities which included design and fabrication of required tooling, test fixtures, and GSE (Ground Support Equipment). A full treatment of the integration and test process on TacSat-3 would be too great for this paper, but major events are listed. Major schedule and mission assurance events include the failure of ARTEMIS during random vibration testing, the delay of the C&DH subsystem (and its subsequent impact on flight software development/testing), and redesign of star tracker placement. As a developmental system many problems were discovered and corrected with the final tally of Problem Failure Reports listed at 184 unique items.

The first delivered item to Kirtland was the ARTEMIS payload. ARTEMIS payload testing was reviewed by the AFRL systems engineering team and the AI&T team, and a decision was made to perform additional random vibration testing to determine survivability on the original focus mechanism design. The test was halted below acceptance levels to allow for a backup rework of the focus mechanism structure. Upon further inspection, however, it was determined the spectrometer had structurally failed. ARTEMIS was shipped back to Raytheon for repair. The required repair was extensive, and resulted in a 9-month delay in schedule.

In parallel, the spacecraft bus was delayed due to developmental issues on the C&DH as well as manufacturing issues with the Power Control Electronics (PCE). A decision to deliver the spacecraft bus early (without the C&DH and with Engineering Model PCE) was made to allow the AI&T team to start their efforts in an attempt to save schedule. The C&DH was subsequently delivered 4 months after the spacecraft bus and the PCE was delivered 6 months after the spacecraft bus. The delays in these two key

components delayed a majority of the AI&T bus system level testing. Ultimately, both the ARTEMIS repair and these components competed for a position on the program schedule's critical path.

As critical components were introduced, the AI&T team discovered normal developmental test issues such as incorrect build vs. documentation, interface discrepancies, software bugs, and various minor design issues. However, a major deficiency in the placement of the star trackers on the ARTEMIS payload was discovered. The original design called for the star trackers to be placed on the same bay pointed aft looking through the gap between two solar panel wings. The edges of the star tracker baffle Earth exclusion zone were close to the edges of the solar wings. It was demonstrated that very low illumination on the solar wing edges would blind the star trackers. A joint team including AFRL, Aerospace Corporation, ATK Space, and Raytheon conducted a design study to review the issues, and the location of the star trackers was changed to minimize the potential for the problem. On-orbit performance has confirmed that the design change was effective.

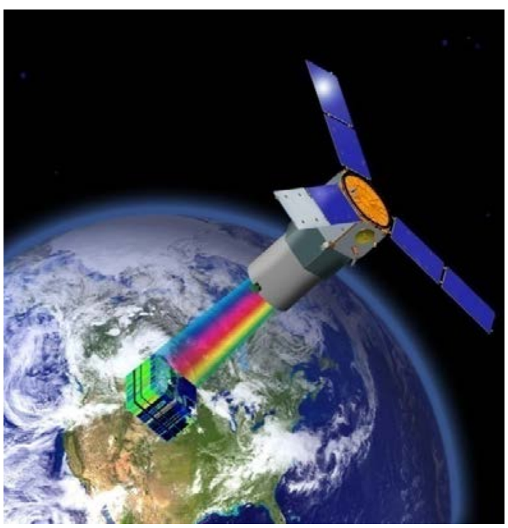


**Figure 5. Artist rendition of TacSat-3: note the deployed solar array configuration**

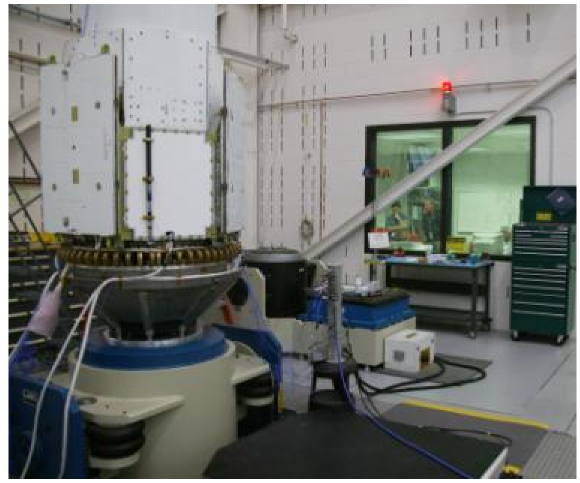


**Figure 6. TacSat-3 in Random Vibration Test**

Functional testing, systems-level thermal vacuum, random vibration testing, and factory compatibility of the communications links were successfully completed and the spacecraft was ready for shipment to NASA's Wallops Island Flight Facility when another anomaly was discovered. With the spacecraft literally on the loading dock in preparation for shipment to the launch site, the manufacturer of the spacecraft transponder used for up-linking commands determined that some parts were not built to specifications by a supplier and could potentially fail during launch. The manufacturer recommended that the parts be replaced. This involved removing the transponder from the spacecraft, shipping it back to the manufacturer for parts replacement and requalification and reinstallation into the satellite. The end result was a three-month delay, which was used by the AFRL team to complete additional functional testing of the spacecraft systems and software. Integration and test was finally completed in March 2009 and the satellite was shipped to Wallops Island.

### *Integration and Test Phase Lessons Learned Highlights*

Integration and test for TacSat-3 was a validation of the AFRL independent AI&T concept. Lessons include a strong validation of adherence to the 'test like you fly' concept, flexibility as delays occur in the development/acquisition phase of the program, commitment to a minimum mission assurance level, and finally the ability to innovate while being mindful of cost and schedule impacts. Finally, experienced test personnel were absolutely key to the mission success. Although new personnel were taught during the course and provided irreplaceable contributions, the key experiences of the AI&T Team Lead to discern the criticality of problems and work around them ensured mission success while managing cost and schedule impacts.

As discussed above, the ability of the original delivery of ARTEMIS to survive launch loads was brought into question due to low margins on the focus mechanism. Original vibration tests were only specified to be performed at the workmanship level to save on cost & schedule. However, after an independent review by the AFRL team, a more representative flight-like vibration test was deemed necessary. This allowed the early identification of not only the focus motor problem, but the failure of the spectrometer. Had this occurred later in the system-level environmental testing, repairs would have been much more costly in terms of impact to the program.

As problems or failures occur in test, the ability to modify the original sequencing of activities becomes critical. The ability to maintain flexibility while maintaining a high level of mission assurance was a key to the TacSat-3 success. This flexibility resulted from open lines of communication that enabled rapid decision making that also took into account the impacts on mission assurance. This flexibility was also balanced with the Program Manager's insistence on a minimum amount of mission assurance. As with any technology development and test program, discovery of previously unknown behavior introduces potential risk and can have negative impacts on cost and schedule. Maintaining mission assurance was key to the decision to relocate the star trackers. There were analyses which showed the original placement was adequate, but tests showed a high likelihood of blinding the star trackers. Although movement of the star trackers caused a significant delay in the program and a major rework of flight hardware, the commitment to mission assurance took priority, leading to a highly successful mission.

This commitment did not stifle innovation, but actually enhanced it. During the star tracker blinding resolution process several options were assessed. Through the combined AFRL, ATA-Aerospace, ATK and Raytheon teams the impact of the move to cost and schedule were minimized. In fact, several software tests were able to be pulled up in priority. Innovation was also demonstrated in the test design through bagging the spacecraft and rolling it outside to track stars while shining lights on solar array simulators. The results of these tests were critical to understanding the impact of the problem.

Innovation was also demonstrated when a parts issue became apparent less than a week from shipment to the launch site. The primary TT&C radio was deintegrated from the spacecraft in less than 2 hours, ready to ship back to the manufacturer. Availability of replacement parts became a major issue, as the TacSat-3 was inherently a lower priority mission. Delays in parts procurement as well as rework queues meant a major schedule (and subsequent cost) impact. The delay could have been greater than a year. A process was developed to 'upscreen' parts from the bad lots, which resulted in the ability to rework the radio prior to other higher priority missions who required new parts. This risk paid off on 19 May 09 with a successful first contact. No problems in the radio have been found.

### *Operations Phase Overview*

Tactical Satellite-3 experiment operations started on 19 May 2009 upon a successful launch from Wallops Island, VA. Mission operations were led by the Air Force Research Laboratory, but included several mission partners throughout the country. The primary mission was to experiment with tactical operations, validate and measure the utility of hyperspectral imagery, and support the secondary experiments. As a new technology capability experiment, mission operations were divided into three distinct phases: Launch and Early Orbit (LEO), Calibration, and Validation phases.

**Figure 7. TacSat-3 Launch**

Launch and Early Orbit is the critical phase of stabilizing the spacecraft and checking out all systems and sensors. This typically requires several weeks of work. Launch and Early Orbit's primary objectives were to launch the space vehicle, ensure the space vehicle met a minimal level of functionality, and finally characterize a minimal level of performance to declare its operational status. One of the mission objectives calls for developing traceability to deliver a new capability on orbit within 7 days; 24 hours of which includes the LEO phase of the mission. As TacSat-3 is

a developmental system, this timeline was deemed to be too aggressive. Additionally, there were legitimate concerns to allow outgassing to preserve the system's optical capabilities. Even with these safeguards, the first image was taken less than 72 hours after launch with all systems functioning within expected parameters.

The actual exit of the Launch and Early Orbit campaign occurred 20 days after launch. The schedule driver was to demonstrate reliable downlink via the high speed rates required for mission execution. The spacecraft was checked out with minimal safety issues, and an initial performance baseline was established. Due to the delay in high speed downlink reliability, AFRL chose to start Calibration Phase activities 7 days after launch.

The Calibration Phase consisted of iterating the system parameters to refine the performance baseline. This phase lasted until 19 Aug 09 (three months after launch). The planned duration of this period was 6 weeks, but delays were a function of the small team used in operations, bad weather at our primary calibration sites, lack of understanding of the severity of ARTEMIS thermal mis-design on the sensor ability to focus and thus to be calibrated, and ensuring we could predict mission performance in the validation phase. At the conclusion of the calibration phase the following items were accomplished:

1. Sensor operations normalized and characterized with temperature sensors
2. Comparison of pre-launch measurements and consistent with post-launch measurements
3. All sensor collection modes functional and provided data consistent with pre-flight estimates
4. Telescope focus established
5. Spectral & radiometric performance quantified
6. Collected data against known calibration target areas
7. End-to-end processing chain validated (spacecraft to scientist)
8. Demonstrate tactical concept of operations baseline to support validation experimentation

The Validation Phase of the mission was primarily to demonstrate the hyperspectral imaging concept in a variety of uses. This phase consisted of tactical testing, evaluation of mission data for military purposes, complete characterization of mission performance, and finally, providing enough statistical data on the technology performance to inform any possible future acquisition. Several lessons in small spacecraft operations were learned or confirmed during this phase. First among these lessons was to demonstrate the value of sufficient margin in the space system design. The spacecraft bus design included intentionally conservative estimates for power generation and usage limitations, resulting in a highly robust power system that has always been power positive during all planned activities. Due to the considerable power margins, the amount of planned experiments was expanded, providing a more successful overall mission.

The validation phase demonstrated sufficient utility along with sufficient margins in order to consider the use of the system after the 1 year AFRL experimentation. While this 'residual' operations phase was not necessarily planned for, it demonstrates a portion of the success of the TacSat-3 mission.

### *Operations Phase Lessons Learned*

Preparation for TacSat-3 mission operations took place over approximately the last 18 months before launch. Four mission ops rehearsals were conducted involving the entire team, as well as several exercises and drills. As with all experimental missions, many lessons were learned despite extensive preparations.

Perhaps the most critical lesson learned from the experiment operations phase was about the role of mission planning, and the structure of the team. The original TacSat-3 ops team structure did not account for mission planning activities other than the normal contact planning done for nominal activities such as stored state of health downlink. As the mission progressed from the LEO phase and checkout activities, it became obvious that the planning activities, including data collect planning, scheduling for CDL downlinks and secondary payload operations, and working in system calibration activities, was a much larger job than originally anticipated – at least a one-and-a-half to two-person job. The structure of the ops team was modified to include a mission planner position, filled by members of the chief engineering team. In addition, a room next door to the TacSat-3 Mission Operations Center was modified specifically to become the planning cell, equipped with mission planning tools and access to vehicle telemetry.

The original TacSat-3 ops team chain of command included a position called the EXCO, or External Coordinator. This position was invented for the TS-3 ops team, intended to be a specialist for interfacing with the many partners of the TacSat-3 team. As the mission

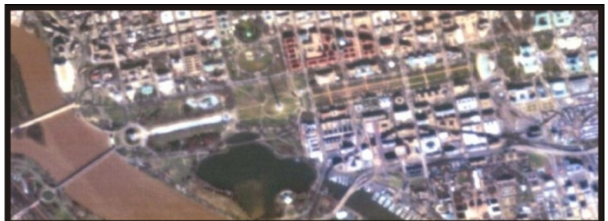
planning role expanded, the External Coordinators became Experiment Coordinators, and their job expanded as well to shoulder most of the duties of experiment and collect planning.

The number of activities going on concurrently during mission operations, especially during LEO, can lead to communication difficulties. This was especially true for TacSat-3, with its large number of external mission partners. Keeping all stakeholders abreast of the current and planned ops required that new tools be put in place to ease planning and communication pathways. A weekly ops meeting with all stakeholders was initiated. A weekly plan was also initiated, containing all activities that the planning team desired to accomplish in a given week. The plan was presented at the meeting for stakeholder input, then published for access by all members of the team. The combination of plan and meeting solved not only the communication and stakeholder input difficulties, but also gave the mission planning cell an invaluable tool for organizing and scheduling objectives.

A second critical lesson learned from TacSat-3 experimental operations involved the role of scripting in operations. Recent AFRL missions have taken advantage of ground scripting to expedite the build of complex commands and to enable system experts to transition out to other duties. Ground scripting allows a minimal crew with less experience to repeatedly generate complex commands with minimal parameter changes quickly and with little chance for human error. An additional benefit of this ability was demonstrated on TacSat-3, where the flexibility of ground scripting provided a work-around in cases where the autonomy portion of the flight software could not be easily changed. Ground scripting allowed commands to be re-built in different sequences with different timing delays, and then the scripts could be re-used later to build other iterations of the same activity. The TacSat-3 team was not large (3-6 people staffing most positions, many of which needed at least on-call coverage 24 hours a day), and it was critical that personnel be used as efficiently as possible. Scripting of many ops activities also allowed for more efficient use of ops team personnel.

The TacSat-3 flight software design contained many task modules as well as tables used by the GNC software. Modules could be interchanged for a new version of the same module, as could tables; however, there was no indication in telemetry which version of a module was in use. The GNC tables had a similar problem: A table used for a given purpose always carried the same name, regardless of which version it was. This situation made configuration control more difficult than it might have been; the lesson learned here was that going forward, modules in use on board should be uniquely identifiable and that information should be available in telemetry.

SUMMARY



U.S. Air Force TacSat-3/ARTEMIS image of the National Mall, Washington, D.C., modified for public release using three of 400+ spectral bands to create a rendering from detailed spectral data.

U.S. Air Force TacSat-3/ARTEMIS image of Kilauea Volcano, Hawaii, modified for public release using three of 400+ spectral bands to create a rendering from detailed spectral data.

**Figure 8. Sample ARTEMIS images**

In summary, TacSat-3 was a successful AFRL small satellite mission, focused primarily on the ARTEMIS hyperspectral sensor (sample images given in Figure 8) and tactical use of small satellites. Lessons learned from the development, I&T, and experimental operations of TacSat-3 and ARTEMIS will be carried forth to future AFRL flight experiments. As technology advances, it demonstrates the utility of small spacecraft to make meaningful impacts in support of our national defense. On 12 Jun 10, the TacSat-3 system was handed over to Air Force Space Command as an operational leave-behind capability.

*Acknowledgments*

The authors would like to acknowledge the efforts of the men and women who made TacSat-3 a reality. But more importantly we hope that all of our efforts go to benefit the men and women who courageously put themselves in harm's way.

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